Femtosecond Laser Inscribed Small-Period Long-Period Fiber Gratings With Dual-Parameter Sensing

Zhong-Ming Zheng, Yong-Sen Yu, Xuan-Yu Zhang, Qi Guo, and Hong-Bo Sun, *Member, IEEE*

***Abstract*— A small-period long-period grating (LPG) with a period of 40μm fabricated in a single-mode fiber by femtosecond laser direct writing has been demonstrated. A series of high-order Bragg resonant peaks of Bragg grating and attenuation bands of LPG can be observed simultaneously in the broadband spectrum range that exhibited different responses to surrounding refractive index, temperature, and axial strain. Meanwhile, we provided a sensitivity matrix to correct the errors caused by temperature in measurements of refractive index and strain to achieve a dual-parameter fiber sensor at high temperature.**

***Index Terms*— Fiber optic sensors, femtosecond laser direct writing, small-period long-period fiber gratings.**

I. Introduction

OPTIC fiber sensors have widely attracted great attention in the past few decades due to their advantages of small size, anti-electromagnetic interference and corrosion resistance [1]–[3]. In real environment, there are many physical factors acting on the sensing fiber, such as strain, temperature, bending, twisting, refractive index (RI) and so on. The signal from the fiber sensing area is actually subjected to the effects of multiple physical factors, therefore, the parameter to be measured cannot be accurately measured. Temperature and strain cross-sensitivity is one of the primary causes of errors associated with practical application of fiber sensors [4]. Therefore, the multi-parameter simultaneous monitoring of optic fiber sensors is of great significance.

Many methods have been proposed to solve cross-sensitivity problem including combination of fiber Bragg gratings (FBG) and long-period gratings (LPG) [5]–[6], reference grating methods and extraordinary designs of fiber material, structure and package [7]–[10]. These solutions are effective in compensating cross-sensitivity. However, the introduction of additional grating structures increases the fabrication cost and complexity. Special designs of sensing units, such as coating suitable polymer materials on the fiber surface or employing core materials with different refractive index, might reduce the thermal stability, mechanical strength and sensitivity of the sensor.

To overcome these problems, we proposed an optical fiber sensor based on small-period long-period grating (SP-LPGs). In the experiment, we found that when the grating period is tens of microns can cause light coupling not only between the forward and backward core mode but between the forward core mode and cladding modes. Before, Shen *et al.* reported a UV inscribed small-period (25μm) long-period grating with unique polarization-dependent dual-peak pairs [11], in which, the 47th-order Bragg resonant peak can be observed. In this letter, a compact SP-LPG with the period of 40μm fabricated by femtosecond laser direct writing (FsLDW) is proposed. FsLDW is a 3D laser processing technology with high spatial resolution [12]–[13], we can precisely control the laser processing area size, shape and direction, and the fabrication process has a high repeatability due to the program control [14], [15]. Based on this method, we can realize strong RI modulation pattern in the fiber core to overcome the weak average RI modulation caused by small duty cycle in the large grating period. We fabricated a grating with short length and the Bragg reflection peaks and attenuation bands of long-period grating both appear in the spectrum. In addition, the sensing abilities of the SP-LPGs for environmental RI, temperature and axial strain have been investigated.

II. Experiments

In the experiment, direct writing of the SP-LPG in standard single-mode fiber (Corning SMF-28) with infrared fs laser pulses was realized with a Ti: sapphire regenerative amplifier laser system (Spectra Physics) operating at 800 nm. The pulse duration and the maximum repetition frequency were 100 fs and 2.5 kHz. The laser beam with pulse energy of 70 nj was focused into the fiber by an oil immersed 60$\times$ Olympus objective (N.A., 1.42). The fiber was set on a computer-controlled 3D translation platform with a motion spatial resolution of 20 nm. The overall translation velocity of the fiber was set at 10μm/s during the fabrication process. After the inscription, the grating region was annealed at 120 °C

Manuscript received July 12, 2017; revised October 3, 2017; accepted October 6, 2017. Date of publication October 10, 2017; date of current version January 8, 2018. This work was supported in part by the National Key Research and Development Program of China and in part by the National Natural Science Foundation of China under Grant 2017YFB1104300, Grant 61590930, Grant 61435005, Grant 51335008, and Grant 61605056. The associate editor coordinating the review of this paper and approving it for publication was Dr. Qiang Wu. *(Corresponding author: Yong-Sen Yu.)*

Z.-M. Zheng, Y.-S. Yu, X.-Y. Zhang, and Q. Guo are with the State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, China (e-mail: yuys@jlu.edu.cn).

H.-B. Sun is with the State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, China, and also with the State Key Laboratory of Precision Measurement and Instruments, Department of Precision Instrument, Tsinghua University, Beijing 100084, China (e-mail: hbsun@tsinghua.edu.cn).

Digital Object Identifier 10.1109/JSEN.2017.2761794

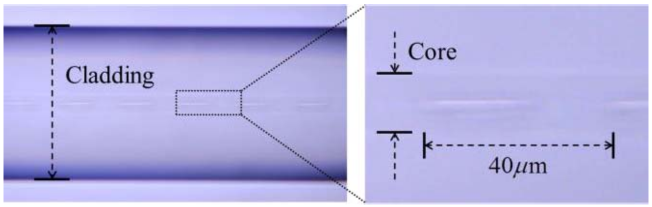

Fig. 1. Microscopic images of femtosecond laser inscribed SP-LPG with period of 40μm.

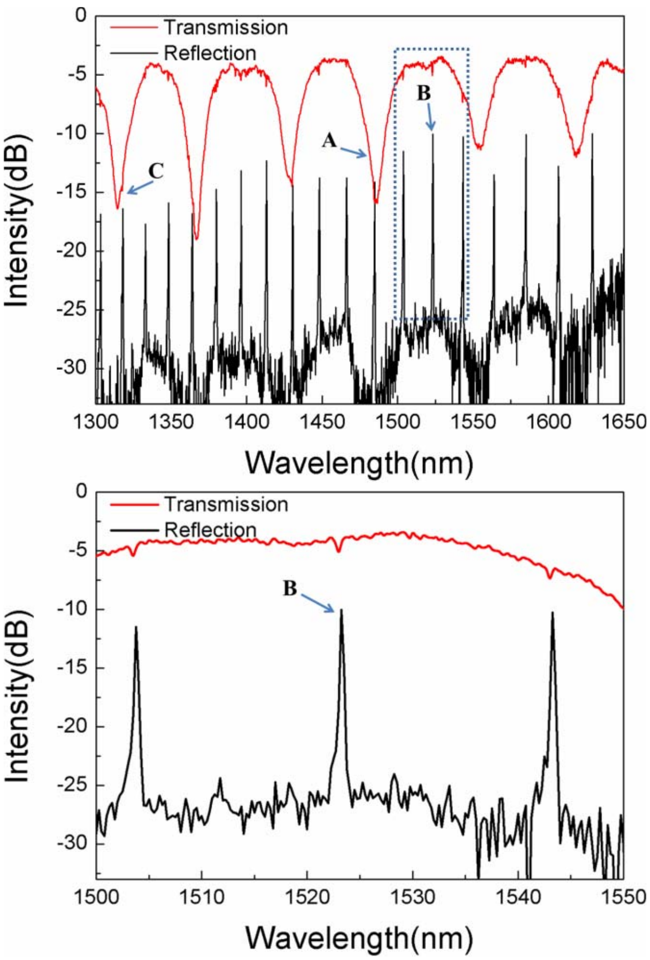

Fig. 2. (a) Transmission and reflection spectra of the SP-LPG. (b) Zoomed-in spectrum around 1523nm, where some small dips corresponding to Bragg resonant peaks can be seen.

for 24h to stabilize the structure. Fig. 1(a) shows the structure of the fabricated SP-LPG with the period of 40 μm and a duty cycle of 0.5. The period number is 75 and the grating length is only 3 mm. The micrograph exhibits that the periodic straight-line RI modulation region along the fiber axis is located in the center of fiber core.

Both the Bragg resonant peaks and attenuation band of the SP-LPG can be clearly observed from 1300 nm to 1650 nm in Fig. 2(a). The side-mode suppression ratio (SMSR) of the strongest Bragg resonant wavelength λ_B at 1522.8 nm was $\sim$17 dB with a full width at half maximum (FWHM) of $\sim$0.4 nm. Three small dips in transmission corresponding to Bragg resonant wavelength including λ_B can be seen in Fig. 2(b). Generally, a longer grating length can enhance the

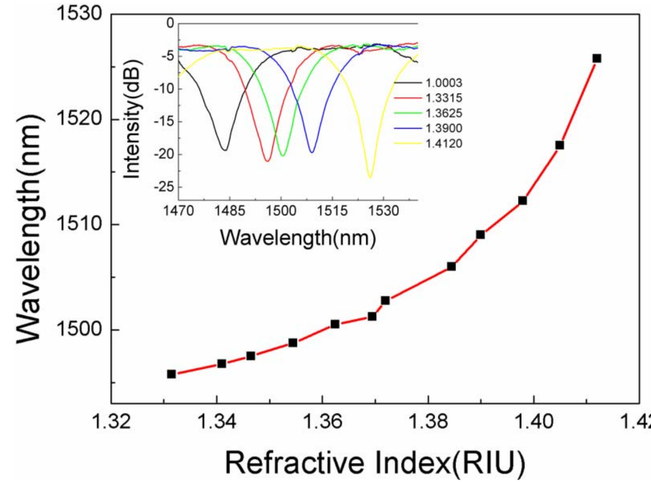

Fig. 3. Relationship between resonant dip wavelength and the surrounding RI. The inset shows the evolution of the transmission spectrum versus to the increasing RI of the surrounding liquid.

Bragg reflectivity and the attenuation dips will become sharper, which helps to improve the resolution of the sensor [16]. However, in our experiment we found that the attenuation dips of LPG will get weak with an excessive increase of number of grating period. So we set the number of grating period and length of the grating to 75 and 3mm to achieve a good performance.

III. Sensing Characteristics and Discussion

After the fabrication, we studied the sensing characteristics of the SP-LPGs, SP-LPG was connected by a broadband light source (Superk Compact, NKT Photonics) and an optical spectrum analyzer (OSA) (AQ6370B, Yokogawa) during the testing process. The transmitted signal and the reflected signal was collected by OSA respectively. The symbol A in Fig. 2(a) corresponds to the attenuation dip in RI measurement. The symbol B and C correspond to the Bragg resonant peak and attenuation dip in temperature and strain measurement. In the experiment, a series of glycerin-water mixed solution with RI range from 1.3315 to 1.4120 was applied in turn to the SP-LPG sensor. The SP-LPG was cleaned in ethanol and deionized water after each measurement to remove the residual chemical from the grating and to recover the original spectrum [17]. Fig.3 shows the resonant wavelength shift of the SP-LPG with different RI. The inset of Fig. 3 shows that the wavelength λ_A exhibited redshift characteristics as the RI increasing in the range of 1.3315–1.4120. The main figure shows that is a non-linear relationship and the shift becomes faster when the RI is close to 1.4120. The average sensitivities of λ_A in the RI range of 1.3315–01.3845 and 1.3845–1.4050 are about 189.8 nm/RIU and 542.8 nm/RIU, respectively. The sensitivity reaches as maximum as 1178.6 nm/RIU in the RI range of 1.4050–1.412.

Besides to the surrounding RI, the temperature and axial strain responses of the SP-LPG were also investigated. Placing the fiber in a tube furnace, temperature was increased from room temperature (24 °C) to 900 °C with an increment

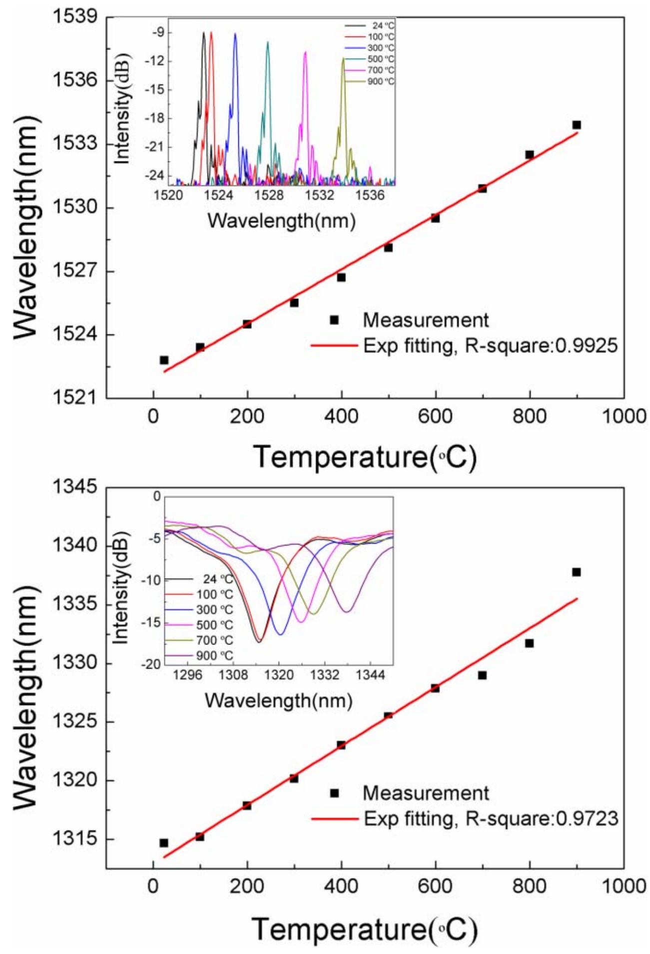

Fig. 4. (a) Relationship between Bragg resonant wavelength and the temperature. The inset shows the evolution of the reflection spectrum versus to temperature. (b) Relationship between resonant dip wavelength and the temperature. The inset shows the evolution of the transmission spectrum versus to temperature.

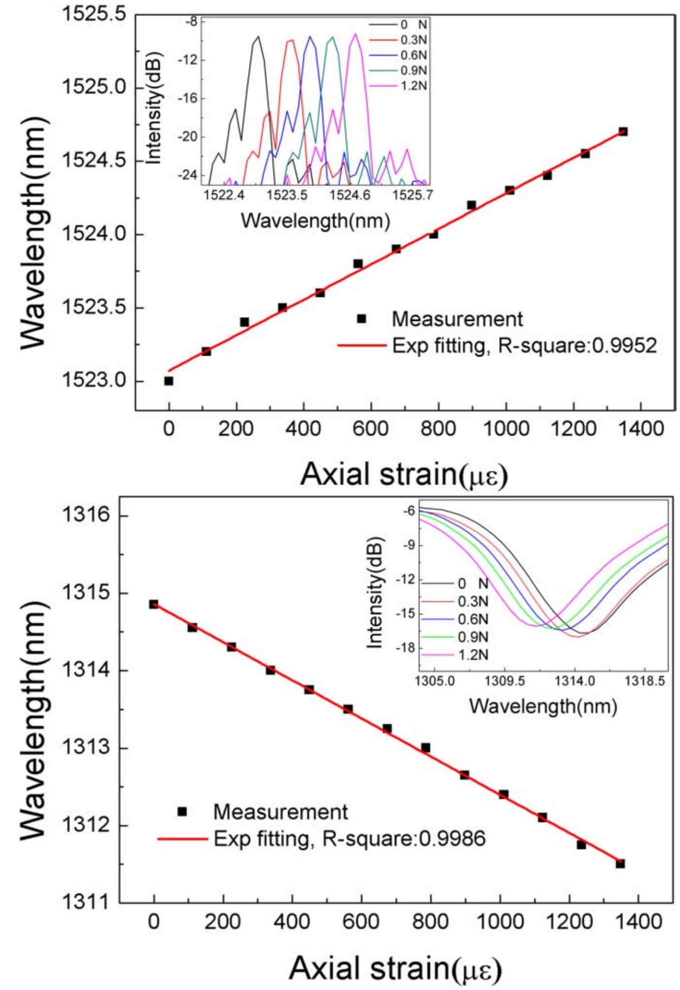

Fig. 5. (a) Relationship between Bragg resonant wavelength and the axial strain. The inset shows the evolution of the reflection spectrum versus to tension. (b) Relationship between resonant dip wavelength and the axial strain. The inset shows the evolution of the transmission spectrum versus to tension.

of 100 °C and the holding time at each temperature point is 10 minutes that is long enough for the stabilization of spectrum and recording the data. Fig. 4(a) shows the temperature response of the 76th-order Bragg resonant λ_{B} at 1522.8 nm. As shown in the figure, the Bragg resonant peak showed an obvious redshift with the temperature increasing. The relationship between wavelength shift of the resonant peak and temperature is linear, which shows a sensitivity of 12.85 pm/°C. As shown in Fig. 4(b), the cladding mode attenuation dip wavelength λ_{C} at 1315 nm has a linear redshift with temperature increasing. Its temperature sensitivity is 25.13 pm/°C.

As shown in Fig.5 (a), the measurement of strain response was realized by adding axial tension to the SP-LPG through a piezoelectric tensometer. The axial strain applied to the fiber could be calculated by equation [18],

$$\varepsilon = F/\pi r^2 E \tag{1}$$

where F is the axial tension, r is the cladding radius, and E is Young's modulus of silica. In the range from 0 $\mu\varepsilon$ to 1400 $\mu\varepsilon$, the relationship between Bragg resonant wavelength λ_{B} and axial strain is linear, which shows a sensitivity of 1.21 pm/$\mu\varepsilon$. Fig. 5(b) shows the cladding mode attenuation dip wavelength λ_{C} changing with axial strain increasing, exhibiting a negative strain sensitivity of -2.46 pm/$\mu\varepsilon$.

Finally, we offered a sensitivity matrix to compensate the error of the cross-sensitivity in the temperature and strain measurement [19]. The relationship between wavelength shifts $\Delta\lambda_{\mathrm{B}}$, $\Delta\lambda_{\mathrm{C}}$ and temperature and strain changes ΔT, $\Delta\varepsilon$ can be written as,

$$\begin{bmatrix} \Delta\lambda_{\mathrm{B}} \\ \Delta\lambda_{\mathrm{C}} \end{bmatrix} = \begin{bmatrix} \mathrm{K_{T1}} & \mathrm{K}_{\varepsilon 1} \\ \mathrm{K_{T2}} & \mathrm{K}_{\varepsilon 2} \end{bmatrix} \begin{bmatrix} \Delta \mathrm{T} \\ \Delta\varepsilon \end{bmatrix}$$

where $\mathrm{K_{T1}}$ and $\mathrm{K_{T2}}$ are the temperature sensitivities of the Bragg resonant peak and LPG resonant minima, respectively. $\mathrm{K}_{\varepsilon 1}$ and $\mathrm{K}_{\varepsilon 2}$ are their strain sensitivities. Substituting the values obtained from experiments into the matrix, the final expression can be written as,

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = \begin{bmatrix} 12.85 & 1.21 \\ 25.13 & -2.46 \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_B \\ \Delta\lambda_{\mathrm{C}} \end{bmatrix}$$

Thus, one can simultaneously obtain the changes of the temperature and the strain when the wavelength changes of the Bragg reflection peak and LPG resonant minima are determined. Similarly, the simultaneous measurement of RI and temperature can also be achieved by this method.

IV. Conclusion

In summary, we experimentally demonstrated a dual-parameter fiber grating sensor based on SP-LPG fabricated by FsLDW. The fabricated SP-LPG with the period of 40 μm shows a series of Bragg resonant peaks and LPG attenuation bands simultaneously. This grating, as one structure, has both FBG and LPFG sensing characteristics, monitoring temperature, strain, RI three parameters. We provided a sensitivity matrix to compensate the error of the cross-sensitivity in the RI and strain measurement under high temperature. Therefore, the proposed sensor can be used for sensing of dual-parameters in high temperature environment. The reduction of the length of the grating also greatly reduces the interference caused by bending in the sensing application and has a great advantage for the small integration of passive optics [20]. This SP-LPG sensor based on FsLDW has the advantages of simple fabrication process, dual-parameter sensing ability and compact size. The SP-LPG is expected to have great practical value in liquefied petroleum gas sensing [21].

References

[1] B. Lee, "Review of the present status of optical fiber sensors," *Opt. Fiber Technol.*, vol. 9, no. 2, pp. 57–79, 2003.

[2] V. Bhatia and A. M. Vengsarkar, "Optical fiber long-period grating sensors," *Opt. Lett.*, vol. 21, no. 9, pp. 692–694, 1996.

[3] A. Kersey *et al.*, "Fiber grating sensors," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1442–1463, Aug. 1997.

[4] M.-J. Yin, B. Huang, S. Gao, A. P. Zhang, and X. Ye, "Optical fiber LPG biosensor integrated microfluidic chip for ultrasensitive glucose detection," *Biomed. Opt. Exp.*, vol. 7, no. 5, pp. 2067–2077, 2016.

[5] X. Zeng, Y. Rao, Y. Wang, Z. Ran, and T. Zhu, "Transverse load, static strain, temperature and vibration measurement using a cascaded FBG/EFPI/LPFG sensor system," in *15th Opt. Fiber Sensors Conf. Tech. Dig.*, vol. 1. May 2002, pp. 199–202.

[6] X. Shu, B. A. L. Gwandu, Y. Liu, L. Zhang, and I. Bennion, "Sampled fiber Bragg grating for simultaneous refractive-index and temperature measurement," *Opt. Lett.*, vol. 26, no. 11, pp. 774–776, Jun. 2001.

[7] W. Yuan, A. Stefani, and O. Bang, "Tunable polymer fiber Bragg grating (FBG) inscription: Fabrication of dual-FBG temperature compensated polymer optical fiber strain sensors," *IEEE Photon. Technol. Lett.*, vol. 24, no. 5, pp. 401–403, Mar. 1, 2012.

[8] Q. Liu, K. S. Chiang, and K. P. Lor, "Condition for the realization of a temperature-insensitive long-period waveguide grating," *Opt. Lett.*, vol. 31, no. 18, pp. 2716–2718, Sep. 2006.

[9] K. Dandapat, S. M. Tripathi, Y. Chinifooroshan, W. J. Bock, and P. Mikulic, "Compact and cost-effective temperature-insensitive bio-sensor based on long-period fiber gratings for accurate detection of *E. coli* bacteria in water," *Opt. Lett.*, vol. 41, no. 18, pp. 4198–4201, 2016.

[10] H.-J. Chen, L. Wang, and W. F. Liu, "Temperature-insensitive fiber Bragg grating tilt sensor," *Appl. Opt.*, vol. 47, no. 4, pp. 556–560, Jan. 2008.

[11] F. Shen, C. Wang, Z. Sun, K. Zhou, L. Zhang, and X. Shu, "Small-period long-period fiber grating with improved refractive index sensitivity and dual-parameter sensing ability," *Opt. Lett.*, vol. 42, no. 2, pp. 199–202, 2017.

[12] R. Fang, A. Vorobyev, and C. Guo, "Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals," *Light Sci. Appl.*, vol. 6, p. e16256, Mar. 2017.

[13] M. Papaioannou *et al.*, "Two-dimensional control of light with light on metasurfaces," *Light Sci. Appl.*, vol. 5, p. e16070, Apr. 2016.

[14] B. Poumellec, D. Matthieu, H. Rudy, B. Evelyne, and B. Bourguignon, "Parity violation in chiral structure creation under femtosecond laser irradiation in silica glass?" *Light Sci. Appl.*, vol. 5, p. e16178, Nov. 2016.

[15] M. Malinauskas *et al.*, "Ultrafast laser processing of materials: From science to industry," *Light Sci. Appl.*, vol. 5, p. e16133, Aug. 2016.

[16] X. Yu *et al.*, "A selectively coated photonic crystal fiber based surface plasmon resonance sensor," *J. Opt.*, vol. 12, no. 1, p. 015005, 2010.

[17] R. Yang *et al.*, "S-tapered fiber sensors for highly sensitive measurement of refractive index and axial strain," *J. Lightw. Technol.*, vol. 30, no. 19, pp. 3126–3132, Oct. 1, 2012.

[18] R. Yang, Y.-S. Yu, Y. Xue, C. Chen, Q.-D. Chen, and H.-B. Sun, "Single S-tapered fiber Mach–Zehnder interferometers," *Opt. Lett.*, vol. 36, no. 23, pp. 4482–4484, 2011.

[19] Z. J. Liu *et al.*, "An optical microfiber taper magnetic field sensor with temperature compensation," *IEEE Sensors J.*, vol. 15, no. 9, pp. 4853–4856, Sep. 2015.

[20] L. Eldada and L. W. Shacklette, "Advances in polymer integrated optics," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 1, pp. 54–68, Jan. 2000.

[21] S. Singh *et al.*, "Synthesis, characterization and liquefied petroleum gas sensing of cobalt acetylenedicarboxylate and its polymer," *Sens. Actuators B, Chem.*, vol. 192, pp. 503–511, Mar. 2014.

Zhong-Ming Zheng received the B.S. degree from the College of Electronic Science and Engineering, Jilin University, China, in 2015, where he is currently pursuing the M.S. degree.

His current research interests include femtosecond laser fabrication of fiber gratings and fiber optic sensors.

Yong-Sen Yu received the M.S. degree in electronics from the Changchun University of Science and Technology, Changchun, China, in 2000, and the Ph.D. degree from the College of Electronic Science and Engineering, Jilin University, Changchun, in 2005.

In 2009, he was an Associate Professor with the State Key Laboratory of Integrated Optoelectronics, Jilin University. His current research interests include laser microfabrication, fiber gratings, and fiber optic sensor.

Xuan-Yu Zhang received the B.S. degree from the College of Electronic Science and Engineering, Jilin University, China, in 2012, where he is currently pursuing the Ph.D. degree.

His current research interests include theory of fiber gratings and fabrication of fiber gratings and the interaction of femtosecond laser and material.

Qi Guo received the B.S. degree from the College of Electronic Science and Engineering, Jilin University, China, in 2016, where he is currently pursuing the M.S. degree.

His current research interests include theory of fiber gratings and fabrication of fiber gratings and the interaction of femtosecond laser and material.

Hong-Bo Sun received the B.S. and Ph.D. degrees in electronics from Jilin University, China, in 1992 and 1996, respectively. He was a Post-Doctoral Researcher with the Satellite Venture Business Laboratory, University of Tokushima, Japan, from 1996 to 2000, and then as an Assistant Professor with the Department of Applied Physics, Osaka University, Osaka, Japan. In 2005, he was promoted as a Full Professor (Changjiang Scholar) with Jilin University. His research interests have been focused on ultrafast optoelectronics, particularly on laser nanofabrication and ultrafast spectroscopy: fabrication of various micro-optical, microelectronical, micromechanical, microoptoelectronic, and microfluidic components and their integrated systems at nanoscale, and exploring ultrafast dynamics of photons, electrons, phonons, and surface plasmons in solar cells, organic light-emitting devices, and low-dimensional quantum systems at femtosecond timescale. So far, he has published over 300 scientific papers in the above fields, which have been cited more than 12000 times, with an H-factor of 55 according to ISI search report.